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Unsteady position control of lean premixed flames in a narrow channel

A. Pieyre*, N. Darabiha, F. Richecoeur

Laboratoire EM2C, CNRS, CentraleSupélec, Université Paris-Saclay, Grande Voie des Vignes, 92295 Chatenay-Malabry cedex, France

Abstract

The stabilization of a premixed methane/air flame in a narrow quartz tube strongly depends on the thermal environment, and particularly on heat transfers between the wall and the gas. Such a coupling induces unsteady behaviours that have only been observed at mesoscale. The aim of this study is then to simulate this coupling by solving simultaneously the one-dimensional equations driving fluid and solid properties with complex chemistry. To validate the numerical simulations, an experimental test case is built. A cylindrical quartz tube has been used with a 5mm inner diameter, chosen above the conventional quenching diameter of the premix. An original unsteady phenomenon is observed experimentally: from a steady reactive configuration, a heat source is activated on the tube's external wall upstream from the flame, lasting few seconds. It makes the flame front move towards upstream until it reaches the maximum wall temperature imposed. The simulations predict well this behaviour proving the ability of the numerical strategy to compute unsteady couplings with different time scales and give access to all the variables as functions of time and space. This highlights new way of controlling a flame position in a channel by a localized and temporary heat input.

Keywords: Mesoscale combustion; Premixed flame; Flame stabilization; Unsteady position control

1. Introduction

Taking advantage of the high energy density of hydrocarbon fuels, micro combustion has a great potential for small generating power devices. One dimensional stability analysis and computation with detailed chemistry [4] and with simple chemistry [2] were made to obtain an overview of the flame stability and to examine the structures of those flames in detail. In the present work we use both experimental measurements and detailed chemistry simulations to study the flame behavior in a tube.

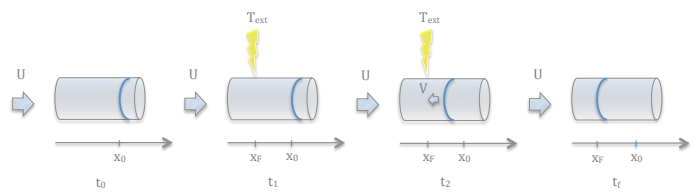

Figure 1: Detailed diagram of the unsteady phenomenon observed : the flame initially stabilized in the tube moves upstream when an external heat source is imposed.

2. Experimental approach

The experiment is a test case for numerical validation. The goal of this experiment is to study the stability of a premix flame inside a cylindrical quartz tube, with a 5mm inner diameter, chosen above the conventional quenching diameter of the premix, so that a flame can evolve inside the tube without external assistance. The mixture, composed of methane and air is injected in the quartz tube from one end of the tube and is ignited at the other end of the tube. The flame evolution is mesured by digital photography (Camera Nikon 7000D – Lens 70-300mm). The wall temperature evolution is measured using a 20 micrometer diameter thermocouple.

An original unsteady phenomenon is observed experimentally. Fig.1 describes this phenomenon : from a steady reactive configuration of the flame in the tube (t_0), a heat source is activated on the tube's external wall at the x_F coordinate (t_1), upstream from the flame front and lasting few seconds. Through a transitory mode the flame front, moves towards the external heat source position (t_2) until it reaches the maximum wall temperature imposed at x_F. The external heat source is then removed and the flame stays stable in x_F (t_F). This phenomenon shows the flame's dependency on thermal exchanges between gas and walls.

Fig.2 shows the flame front speed during this unsteady phenomenon. It can be seen that the flame front speeds up to a maximum value and then stabilizes itself once the x_F coordinate has been reached, after about 6s. This delay time depends on the distance between the initial flame front position and the heat source.

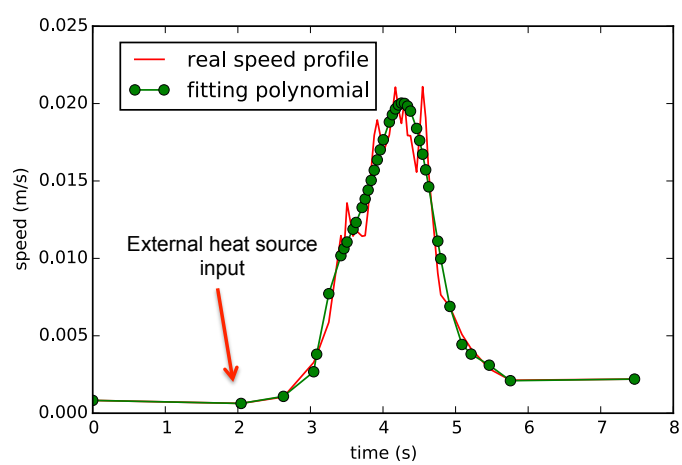

Figure 2: The flame front speed variation during the unsteady phenomenon. The flame speed increases to reach a peak and then decreases to reach the stabilization point.

3. Numerical approach : 1-D computations with detailed chemistry

To understand the flame dynamics with flame-wall structure coupling, a theoretical analysis was carried out. A fortran program for modeling the unsteady behaviour of the one-dimensional premixed flame called REGATH [1] with the GRI kinetic model was used. The numerical method used to solve the equations governing the flame propagation is a combination of a Newton's method and time integration.

The equations governing unsteady one-dimensional flame propagation [3] may be written for gas (1) and solid (2) energy and species mass fonction (3):

$$\rho u \frac{\partial H_G}{\partial x} = \frac{\partial}{\partial x}\left[\lambda_G \frac{\partial T_G}{\partial x}\right] - \sum_{k=1}^{K} \rho Y_k V_k H_k - \frac{2\pi r_i}{\pi r_i^2} h_i (T_G - T_S) \quad (1)$$

$$\rho_S c_{ps} \frac{\partial T_S}{\partial t} = \frac{\partial}{\partial x}\left[\lambda_S \frac{\partial T_S}{\partial x}\right] - \frac{2r_e}{r_e^2 - r_i^2} h_e (T_S - T_A) + \frac{2r_i}{r_e^2 - r_i^2} h_i (T_G - T_S) \quad (2)$$

$$\rho u \frac{\partial Y_k}{\partial x} = -\frac{\partial}{\partial x}\left[\rho Y_k V_k\right] + \dot{\omega}_k W_k \quad (3)$$

In these equations, x is the spatial coordinate, T the temperature, Y_k the mass fraction of the kth species, u the velocity of the fluid premix, ρ the mass density, W_k the molecular weight of the kth species, c_{P_k} the constant pressure heat capacity of the kth species, λ the thermal conductivity, H_k the gas total enthalpy of the kth species, V_k the diffusion velocity of the kth species, r_i and r_e internal and external radius of the tube, h_i and h_e internal and external heat transfert coefficients.

The boundary conditions are :

$x \to -\infty$, $T_{GAS} = T_{WALL} = T_0$, $Y_k = Y_{k_0}$, $\dot{M} = \rho V$.

$x \to +\infty$, $\frac{\mathrm{d}T_{GAS}}{\mathrm{d}x} = \frac{\mathrm{d}T_{wall}}{\mathrm{d}x} = \frac{\mathrm{d}Y_k}{\mathrm{d}x} = 0$

The aim here is to reproduce the unsteady phenomenon observed experimentaly, by imposing a temperature peak upstream from the flame front in REGATH. The results highlight the heat exchange between the wall and the unburnt gases by showing a growing temperature peak in the wall's temperature profile, and a flame front moving towards this peak. The external temperature profile imposed may be written as follows:

$$T_A = T_{ext_0} + (T_{max} - T_{ext_0}) exp(\alpha (x - x_F)^2)$$

With $T_{ext_0} = T_{ext} = 298.0$ K, $T_{max} = 2000$ K, $\alpha = 40.0$ et $x_F = 26$ cm.

Fig.3 shows the wall (e.g. black curve) and gas (e.g. red curve) temperature profile for several iterations progress. The wall and gas temperature profiles, show two peaks, one principal peak located at the flame front, and a secondary peak, where the temperature increases as the iterations progress, and which represents the external heat source. The wall conveys the heat to the gas, which is then preheated and accelerated.

It can be seen clearly in Fig.3 that the flame front moves towards the wall's temperature secondary peak upstream. The flame front stabilizes itself at the x_F coordinate of the external temperature profile imposed after a large number of iterations.

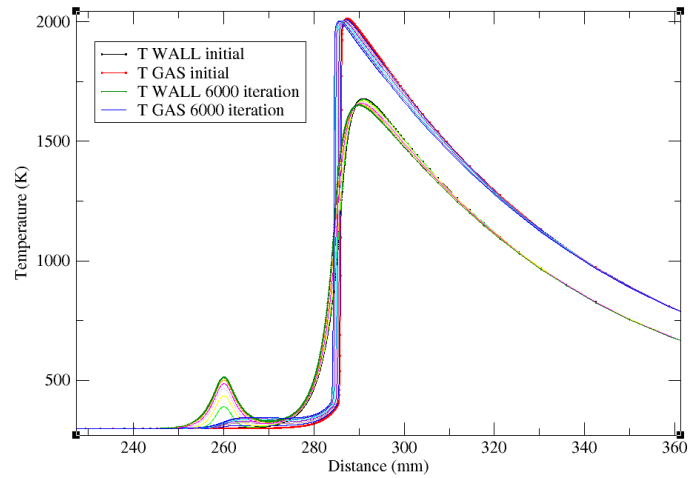

Figure 3: Temperature profile of the gas and wall at several iteractions progress.

This global view on Fig.3 allows to assess the order of temperature's magnitude of the phenomenon.

4. Conclusion

An analytical solution is obtained for flame propagation. It is shown that the one dimensional computation with detailed chemistry, that takes in account the flame-wall coupling, reproduces well the unsteady phenomenon observed experimentally.

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